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Estimating windblown PM-10 emissions from vacant urban land using GIS

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Abstract

This paper presents a Geographic Information Systems (GIS)-based methodology to estimate annual area-wide airborne particulate matter with an aerodynamic diameter of less than 10 μm (PM-10) emissions, and identify zones with high emissions in order to efficiently implement mitigation strategies. Application of the methodology is demonstrated using the land disposal boundary within Clark County, NV as the study area, which is currently classified as a non-attainment area by United States Environmental Protection Agency (US EPA). The estimated PM-10 emissions depend on the extent of disturbed vacant land area, undisturbed vacant land area, emission factors by soil group, and wind speeds. Portable wind tunnel field test data were used to estimate emission factors at 78 sites in the study area. Portable wind tunnel results were categorized by the wind speed range and the corresponding site soil group in order to estimate emission factors by soil group and the wind speed range. Wind speed data were obtained from the Clark County Health District's air quality monitoring stations. The proximal area over which the wind speeds are same is obtained by constructing "Thiessen" polygons around each wind speed monitoring station. PM-10 emissions were estimated as a function of the extent of disturbed vacant lands, the measured or estimated erodibility of the soil surfaces, and the intensity, duration and frequency of erosive wind events.

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1. Introduction

Potential health hazards due to particulate air pollution are a significant concern in both urban areas and rural areas in the United States. Several airsheds are currently classified by United States Environmental Protection Agency (US EPA) as non-attainment areas for airborne particulate matter with an aerodynamic diameter of less than 10 μm (PM-10). Non-attainment areas are identified based on National Ambient Air Quality Standards (NAAQS) set by the Clean Air Act Amendments (CAAA) of 1990. As per the standard, areas with an annual average concentration of 50 $\mu g/m^3$ and an average 24-h concentration of 150 $\mu g/m^3$ are considered as non-attainment areas. Studies conducted by US EPA indicate that emissions of PM-10 based on estimates of anthropogenic emissions, which include fuel combustion sources, industrial processes, and transportation sources account for only 6% of the total PM-10 emissions nationwide [1]. Thus, PM-10 emissions are mainly from natural and miscellaneous sources such as fugitive dust (unpaved and paved roads), agricultural and forestry activities, wind erosion, wildfires, and managed burning. Potential solutions to mitigate these emissions include (but are not limited to) the following.

(1) Control emission from construction sites by consolidating building and grading permits, implementing dust control management practices, inspection of construction vehicles, and issuing separate trenching permits;
(2) Reduce emissions from vacant disturbed lands by application of dust control measures;
(3) Pave unpaved roads or limit the use of unpaved haul roads and parking areas;
(4) Control emissions from paved roads by cleaning streets and shoulder stabilization;
(5) Encourage use of alternate fuel vehicles and reformulated fuels;
(6) Restrict use of recreational vehicles on public lands;
(7) Restrict construction of new wood-burning fireplaces.

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Clark County, NV, which includes Las Vegas area, is currently classified as a non-attainment area by US EPA. The region has exceeded the NAAQS for PM-10 multiple times over the past decade [2]. Chemical mass balance studies have shown that a significant portion of these emissions is of geologic origin. The two main geologic sources are emissions arising from construction activity, and wind-blown dust from disturbed vacant lands. Responsible agencies are working to establish methods and schedules to mitigate the air pollution problem, and to attain and maintain PM-10 NAAQS as expeditiously as practical in the region. Agencies need to estimate the annual area-wide PM-10 emissions and identify the zones and appropriate causes of high emissions in order to implement necessary control measures.

Literature documents development of several models to estimate area-wide emissions due to wind erosion. The model developed by Gillette and Passi [3] was one of first in this area. However, none of the models developed, to date, explore the capabilities afforded by Geographic Information Systems (GIS) software in developing such models. This paper presents a GIS-based methodology to estimate PM-10 emissions by soil group of the study area. The soil group could either be based on the soil properties and composition or it could be based on the wind erodibility factor. It has to be noted that the wind erodibility factor for two polygons in the same soil group based on soil properties and composition may not be the same. Thus, estimates could vary based on whether soil properties and composition or wind erodibility factor was used to classify polygons into soil group. Magnitudes and locations of estimated PM-10 emissions depend on the estimated extent of disturbed vacant lands, on the measured or estimated erodibility of the soil surfaces, and on the intensity, duration and frequency of erosive wind events.

2. GIS-based methodology

The proposed methodology explores the capabilities afforded by GIS in order to estimate PM-10 emissions for the study area. The methodology is discussed using Clark County, NV as an example study area. It includes eight steps:

(1) Create study area coverage;
(2) Generate soil coverage;
(3) Create wind speed monitoring station coverage and identify their proximities to soil group coverages;
(4) Identify the location coordinates (township and range, or book and section), vacant area, soil type based on soil properties and composition, and Wind Erodibility Group (WEG) based on the wind erodibility factor of each polygon;
(5) Identify soil type and WEG of each wind tunnel site;
(6) Estimate emission factors by soil group;
(7) Obtain wind speed data for a particular design period (typically a design day or design year) and estimate PM-10 emissions in each polygon by combining wind speed data with soil group emission factors;
(8) Display emissions in each polygon as a GIS coverage, or sum emissions for an area-wide estimate.

Steps 1–5 in the methodology were used to estimate the extent of disturbed vacant land area, undisturbed vacant land area, and identify the corresponding wind speed monitoring station of a polygon in the study area. Step 6 deals with estimating emission factors using data collected at portable wind tunnel sites. PM-10 emissions for each polygon in the study area are estimated in Step 7. Emissions in all polygons are either mapped or summed in Step 8. In the following subsections, each step of the methodology is discussed in detail.

2.1. Step 1: create study area coverage

As stated before, Clark County, NV is used as the study area to demonstrate the working of the model. The study area includes only the area within the current US Bureau of Land Management's declared land disposal boundary, a zone around the urban core of Las Vegas within which federally owned lands are made available for development via auction. The basis for this coverage is the "township, range and section" coverage of Clark County. A single book number corresponds to a specific township and range and there are 36 sections in each "book", each section approximately covering 1^2 mile. GIS coverage is created by identifying all "books" and "sections" within the land disposal boundary.

The database containing disturbed vacant land area and undisturbed vacant land area of each "book" and "section" was collected for a given year and month from the Clark County Department of Comprehensive Planning (CCDCP). CCDCP performs aerial photographic surveys of its lands twice a year. The actual amounts of vacant land area, and the proportion disturbed may vary from day-to-day based on amount of construction activity. However, for simplicity, it was assumed that the total vacant land area, disturbed vacant land area and undisturbed vacant land area of each "book" and "section" is constant during all the days in the study year.

2.2. Step 2: create soil coverage

The soil coverage was generated based on the data downloaded from the National Soil Survey Geographic (SURGO) database maintained by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Soil Survey Division. The mapping bases are Orthophotoquads. Data are collected and archived by USDA and its contractors in 7.5-min topographic quadrangle units and distributed as a complete coverage for a soil survey area usually consisting of 10 or more quadrangle units [4]. The database consists of digital geo-referenced spatial data, attribute data and metadata.

The geo-referenced spatial data are spatial objects such as polygons, lines, points and nodes whose coordinates represent real location on the Earth's surface. The Map Unit Interpretations Record provides the attributes for the database. The data contain both estimated and measured data on the physical and chemical soil properties, and soil interpretations for engineering, water management, recreation, agronomic, and wildlife uses of the soil. The Map Unit Interpretations Record data consists of tables that include (but are not limited to) soil component information, soil characteristics, taxonomic classification, map unit symbols, and WEG. The metadata describes the content, quality, condition, history and other characteristics of data.

The soil coverage is generated using the downloaded spatial data and attribute data pertaining to map unit soil symbol, detailed soil composition and its area, and, the WEG. The soil coverage generated from the SURGO database is larger than the study area. Soil composition of each polygon is expressed in terms of the name of composition, percent of composition and area of composition within the polygon. The WEG is based on the major soil composition of the top soil layer in the polygon.

2.3. Step 3: create wind speed station coverage and identify their proximities to soil group coverages

Hourly average wind speed data were made available to the authors by the Clark County Health District, Air Pollution Control Division (CCHD-APCD, now the Clark County Department of Air Quality and Environmental Management, CCDAQEM) from information collected by the District's air quality monitoring station network. A point coverage is created using the air quality monitoring station location data. The boundary of this coverage is set same as that of the study coverage. Only wind speed monitoring stations within the study area are considered.

Wind speed data for the Clark County PM-10 State Implementation Plan's (SIP) design year 1999 collected at each of these air quality monitoring stations was obtained from CCHD-APCD hourly average data. The location of wind speed monitoring stations and the proximity of each station in the study area are shown in Fig. 1. The proximal area over which wind speeds were considered the same was obtained by constructing "Thiessen polygons" around each wind speed monitor station. "Thiessen polygons" are individual regions of wind speed influence around each monitoring station. Any location within a particular "Thiessen polygon" is nearer to that polygon than to any other polygon. Wind speed at any point within this polygon is assumed to be the same as that observed at the wind speed monitor station for the polygon.

2.4. Step 4: identify book, section, vacant area, general soil type and WEG of each polygon

The study area coverage created in Step 1 is overlaid on the "Thiessen" polygon coverage created from the wind speed monitor station point coverage. The "book", "section" and vacant land area of each polygon belonging to each wind speed monitor station are identified. The soil coverage created in Step 2 is overlaid on the resulting coverage to generate a new coverage. The polygon attribute table of the new coverage contains data pertaining to "book", "section", vacant land area, disturbed vacant land area, undisturbed vacant land area, general soil type and WEG of each polygon belonging to each wind speed monitor station.

Using the vacant land area, disturbed vacant land area, and undisturbed vacant land area obtained above could lead to erroneous estimates of PM-10 emissions. These errors could occur because the vacant land area, disturbed vacant land area, and undisturbed vacant land area are attributes available in the "info" tables but are not adjusted to each polygon obtained due to the overlay. For example, consider a polygon in the proximity of wind speed monitor station 1 whose area is 50 acres (Fig. 2(i),

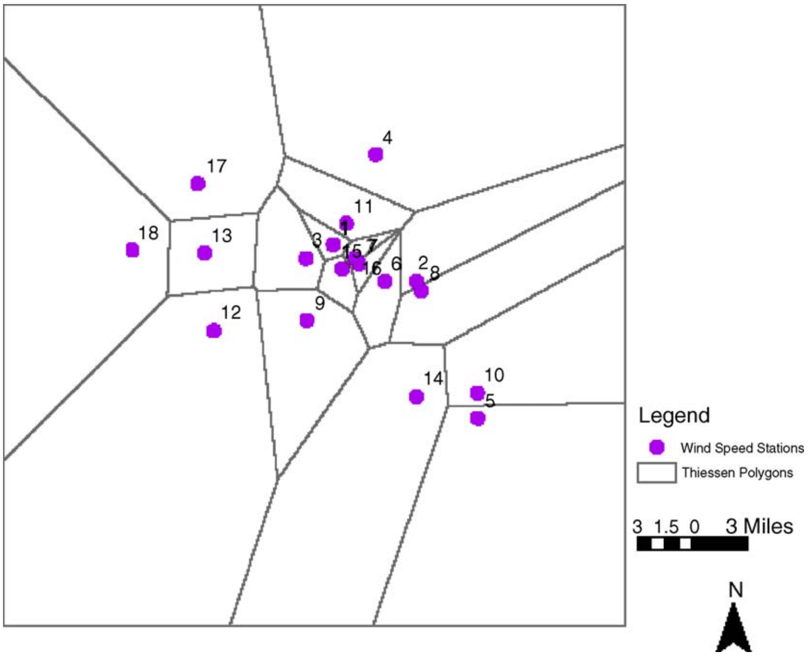

Fig. 1. Wind speed monitor stations and the proximal areas defined by Theissen polygons.

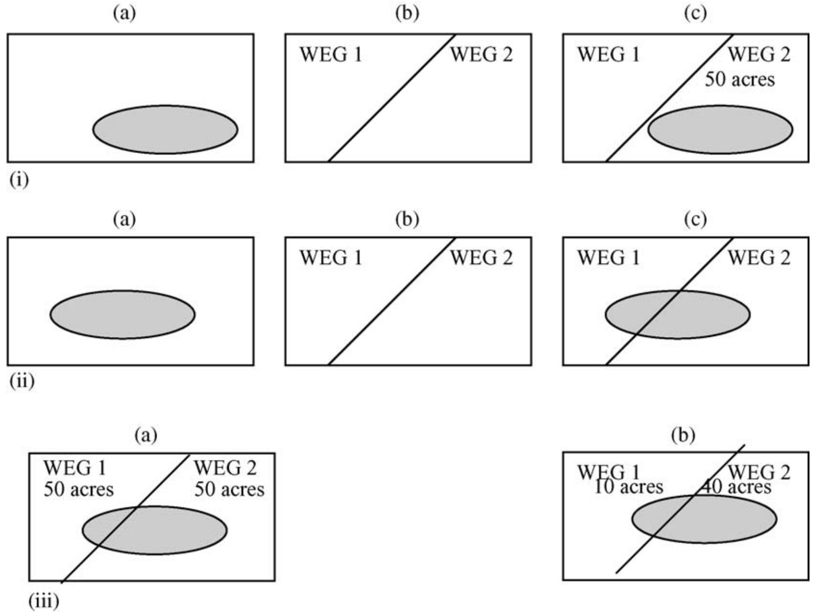

Fig. 2. Allocation of vacant land area to polygons. (i) Using spatial overlay to allocate vacant land area to one polygon: (a) vacant land area (shaded), (b) soil coverage, and (c) spatial overlay. (ii) Using spatial overlay to allocate vacant land area to two polygons: (a) vacant land area (shaded), (b) soil coverage, and (c) spatial overlay. (iii) Incorrect and correct allocation of vacant land area to two polygons: (a) incorrect assignment of proportional entire vacant land area to both groups and (b) correct assignment of vacant land area to both groups.

a). When the study coverage and soil coverage are overlaid on this polygon, the 50-acre polygon is divided into several small polygons. Each small polygon has its area, data from the study coverage such as "book", "section", vacant land area, disturbed vacant land area and undisturbed vacant land area, and data from the soil coverage such as general soil type, WEG, etc. It might so happen that two small polygons could have exactly the same "book", "section", and vacant land area as tabulated data are copied to the new table. However, in fact, the entire vacant land area in a particular section could fall in any one of the small polygons (Fig. 2(i)), or may have been distributed amongst the polygons (Fig. 2(ii)). An overly simplistic method of assignment of vacant land area might, in Fig. 2(ii) incorrectly assign the entire vacant land area to both polygons. To solve this problem, a program was written in the C programming language to approximately adjust the vacant land area, disturbed vacant land area, and undisturbed vacant land area among the small polygons with common "book" and "section" number in proportion to their areas (Fig. 2(iii)). This avoids duplication and overestimation of vacant land areas, hence, avoids overestimation of PM-10 emissions.

2.5. *Step 5: identify soil type and WEG of each wind tunnel site*

A GIS coverage with locations of all portable wind tunnel sites is created using the geometric coordinates of each site. Fig. 3 shows the locations of the wind tunnel sites. The soil coverage is then overlaid on the portable wind tunnel sites coverage to generate a new coverage. The resulting point coverage attribute table consists of data pertaining to general soil type, soil type name and WEG of each portable wind tunnel site. Each site is assigned a general soil type that ranges from 1 to 9 based on its major (three-digit) soil type. These are based on the soil survey study conducted by Speck and Mckay [5] for the Las Vegas area.

PM-10 emissions estimates can be calculated either using the general soil type or the WEG. The main drawback of estimating PM-10 emissions based on the general soil type is that one has to manually assign or write a code to identify the general soil type based on the major (three-digit) soil type. These are not pre-established values based on soil survey. Data indicate that the general soil type may not be the same for two polygons with the same WEG. Aside from this, emissions are mainly due to wind erosion. Hence, it is felt that using emission factors based on WEG would yield realistic results rather than the general soil type. In general, there are 10 numeric WEGs designated 1–9 and 4L. The procedure in Step 6 illustrates the estimation of emission factors by soil group. The developed tool has the capability to estimate emission factors by general soil type and wind speed range or by WEG and wind speed range.

2.6. *Step 6: estimate emission factors by soil group*

The steady-state PM-10 (flux) emissions rate and "spike" emissions rate per unit of each general soil group or WEG, classified by wind speed range, are estimated using data collected at portable wind tunnel test sites. "Spike" emissions represent high initial emissions rates observed in the first 1–2 min of a portable wind tunnel test run, followed by lower, steady-state emissions for the rest of the run. Spike data were separated from steady-state data to avoid overestimating hourly emissions when using

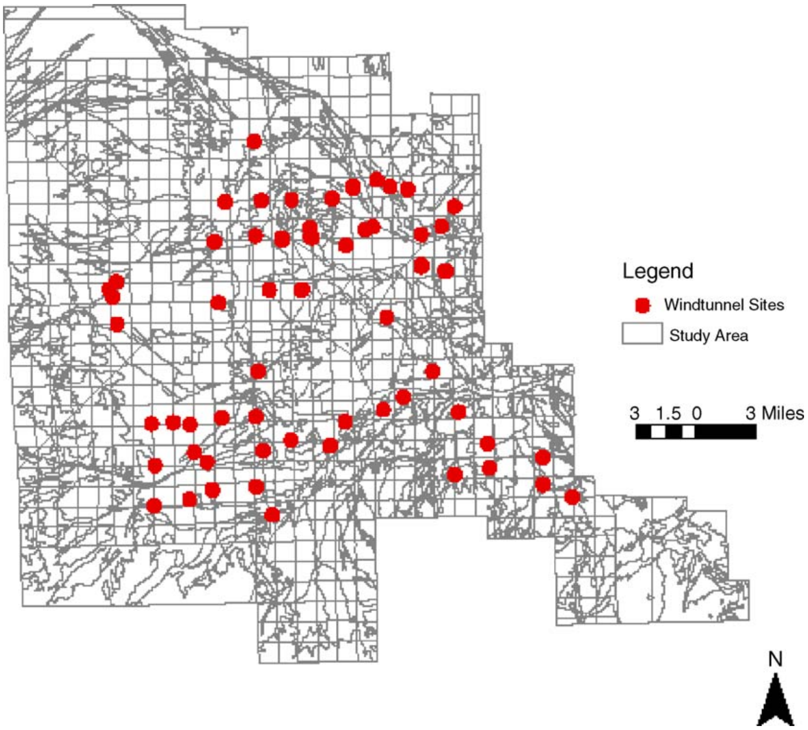

Fig. 3. Portable wind tunnel field sites in the study area.

emission factor data collected from 10 min portable wind tunnel runs.

Measured wind tunnel wind speeds are reported as estimates for 10 m height, based on measurements at the wind tunnel centerline of 7.62 cm. The correction from 7.62 cm to 10 m was done using the measured near-surface bare soil aerodynamic roughness. Detailed discussion about the wind tunnel tests can be found in the PM-10 State Implementation Plan for Clark County [6].

Emissions factor data collected at sites with same general soil group or WEG are first classified into two major categories: (1) collected at a portable wind tunnel sites in unstable (disturbed) areas and (2) collected at portable wind tunnel sites in stable (undisturbed) areas. "Unstable" areas were identified as lands lacking surface crusts or with insufficient coverage of aerodynamic sheltering elements. Sheltering elements could be non-erodible rock, flat vegetation, or upright vegetation. "Stable" areas were identified as land with either crusted surfaces or with sufficient coverage of aerodynamic sheltering elements.

The steady-state fluxes in stable (or unstable) areas for each soil group are the geometric mean of all the flux emissions in a wind speed range collected at the same soil group. The spike emissions in stable or unstable areas are the geometric mean of all the spike emissions in a wind speed range collected at the same soil group. Geometric means are computed by log-transforming the emissions factor data, summing, dividing by the total number of samples collected in disturbed areas in the given wind speed range, and then back transforming the result. Log-transforming the emissions factor data helps avoid right skew extreme outliers.

The above discussion to estimate flux emission factor ($\mathrm{Flux}_{\mathrm{s,w}}$) and spike emission factor ($\mathrm{Spike}_{\mathrm{s,w}}$) for stable (or unstable) areas of soil group 's' in wind speed range 'w' can be mathematically represented using the following equations.

If $n_{\mathrm{s,w}} > 1$,

$$\mathrm{Flux}_{\mathrm{s,w}} = \exp\left(\frac{\sum_i \ln(\mathrm{Flux}_{\mathrm{s,w},i})}{n_{\mathrm{s,w}}}\right) \tag{1}$$

$$\mathrm{Spike}_{\mathrm{s,w}} = \exp\left(\frac{\sum_i \ln(\mathrm{Spike}_{\mathrm{s,w},i})}{n_{\mathrm{s,w}}}\right) \tag{2}$$

where $\mathrm{Flux}_{\mathrm{s,w},i}$ = flux emission factor of sample i in stable (or unstable) areas of soil group 's' in wind speed range 'w'; $\mathrm{Spike}_{\mathrm{s,w},i}$ = spike emission factor of sample i in stable (or unstable) areas of soil group 's' in wind speed range 'w'; $n_{\mathrm{s,w}}$ = number of samples collected in stable (or unstable areas) of soil group 's' in wind speed range 'w'.

The above discussed equations are used to compute emission factors if the number of samples in any soil group (stable or unstable areas) and wind speed range category is at least 2. Table 1(A) illustrates the computation of flux and spike emissions factors for stable conditions of WEG 5 and wind speed range 25–30 mph. The number of samples collected in this wind speed range is 3. Flux and spike in the table are the flux and spike emissions for each sample obtained from the wind tunnel runs.

If the number of samples collected in any soil group (stable areas or unstable areas) and wind speed range category is less than 2, then the flux emission factor ($\mathrm{Flux}_{\mathrm{s,w}}$) and spike emission factor ($\mathrm{Spike}_{\mathrm{s,w}}$) for stable (or unstable) areas of soil group 's' are computed based on the number of samples in stable (or

Table 1
Example computation of flux and spike emission factors

Sample	WEG	Condition	Wind speed	Flux	Spike	Ln (Flux)	Ln (Spike)
(A) Computing flux and spike emission factor for WEG 5 and wind speed range 25–30 mph[a]							
1	5	Stable	26	0.01904	0.00385	−3.96135	−5.55989
2	5	Stable	28	0.00448	0.00077	−5.40793	−7.17055
3	5	Stable	29	0.00598	0.00101	−5.11939	−6.90036
Average						−4.82956	−6.54360
Exp (average)						0.00799	0.00144
(B) Computing average flux and spike emission factor over several WEG in wind speed range 35–40 mph (for use in WEG 4–6)[b]							
1	4	Stable	36	0.00064	0.00037	−7.35597	−7.89839
2	5	Stable	38	0.00290	0.00117	−5.84164	−6.75074
3	6	Stable	37	0.00542	0.00149	−5.21752	−6.51007
4	6	Stable	39	0.01614	0.00287	−4.12663	−5.85249
Average						−5.63544	−6.75292
Exp (average)						0.00357	0.00117

Note: Flux and flux emission factor are in tonnes/acre/h, spike and spike emission factor are in tonnes/acre. Units are in US customary units (1 tonnes = 2000 pounds; 1 acre = 43,560 square feet).

[a] Number of records = 3 (i.e., >1); flux emission factor = exp (average of ln (Flux)) = 0.00799; spike emission factor = exp (average of ln (Spike)) = 0.00144.

[b] Number of records = 1 (i.e., <1); flux emission factor = exp (average of ln (Flux)) = 0.00357; spike emission factor = exp (average of ln (Spike)) = 0.00117.

unstable) areas in wind speed range ‘w’. This can be mathematically represented using the following equations.

If $n_{s,w} \neq 1$ and $n_w > 1$,

$$\text{Flux}_{s,w} = \exp\left(\frac{\sum_i \ln(\text{Flux}_{w,i})}{n_w}\right) \quad (3)$$

$$\text{Spike}_{s,w} = \exp\left(\frac{\sum_i \ln(\text{Spike}_{w,i})}{n_w}\right) \quad (4)$$

where $\text{Flux}_{w,i}$ = flux emission factor of sample i in stable (or unstable) areas in wind speed range ‘w’; $\text{Spike}_{w,i}$ = spike emission factor of sample i in stable (or unstable) areas in wind speed range ‘w’; n_w = number of samples collected in stable (unstable) areas in wind speed range ‘w’.

Table 1(B) illustrates the computation of flux and spike emissions factors for stable conditions of WEG 4 and WEG 5 in wind speed range 35–40 mph when the number of samples collected in WEG 4 and WEG 5 in wind speed range 35–40 mph is 1. The flux and spike emission factors for WEG 4 and WEG 5 in wind speed range 35–40 mph are computed using flux and spike emissions obtained from field in any WEG (in this case, WEG 4, WEG 5, and WEG 6) in this wind speed range. Thus, the computations in this case are based on all four samples collected in the 35–40 mph wind speed range. However, when computing the flux and spike emissions factors for stable conditions of WEG 6 and wind speed range 35–40 mph, only samples 3 and 4 should be considered in the computations.

If the number of samples collected in stable (or unstable) area of soil group ‘s’ in wind speed range ‘w’ is less than or equal to 1 and if the number of samples collected in stable (or unstable) areas in wind speed range is less than or equal to 1, then the flux emission factor ($\text{Flux}_{s,w}$) and spike emission factor ($\text{Spike}_{s,w}$) for stable (or unstable) areas of soil group ‘s’ are computed considering all the samples in the study area. This can be mathematically represented using the following equations.

If $n_{s,w} \neq 1$ and $n_w \neq 1$,

$$\text{Flux}_{s,w} = \exp\left(\frac{\sum_i \ln(\text{Flux}_i)}{n}\right) \quad (5)$$

$$\text{Spike}_{s,w} = \exp\left(\frac{\sum_i \ln(\text{Spike}_i)}{n}\right) \quad (6)$$

where Flux_i = flux emission factor of sample i (any site and wind speed range); Spike_i = spike emission factor of sample i (any site and wind speed range); n = number of samples collected in site l.

Although direct comparison is complicated by differences in measurement methods and in measured particle size ranges, the measured PM-10 fluxes for the Las Vegas study area [6] are higher than arid lands values reported for four studies and lower than two others (Table 2) [3,7–10].

In general, spike emission factors are lower than flux emission factors as they represent high initial PM-10 emissions rates for a very short time (typically 1–2 min). After this spike period, PM-10 emissions decline to much lower steady-state values [6]. PM-10 emissions factors in this study represent the lower steady-state fluxes after the observed spike event.

2.7. Step 7: estimate PM-10 emissions

The data obtained from the previous steps is used along with wind speed data collected during the study year to estimate PM-10 emissions. Estimating PM-10 emissions includes the following sub-steps.

(A) Choose a method for analysis based on soil group:
  1. Soil type;
  2. WEG

(B) Consider wind speed data during the study year at wind speed monitoring station 1.

Table 2
Comparison of average reported wind erosion flux in Las Vegas study area to literature reports cited in Chow and Watson [11]

Study or data source	Reference number	Flux (g/m^2/s)	Flux (tonnes/acre/h)	Participate size range
Gillette and Passi (1988)	[3]	3.0×10^{-5}	4.8×10^{-4}	TSP, <30–50 μm
Nickling and Gillies (1989), disturbed	[7]	9.8×10^{-4}	1.6×10^{-2}	TSP, with 95% <10 μm
Nickling and Gillies (1989), undisturbed	[7]	1.8×10^{-4}	2.9×10^{-3}	TSP, with 95% <10 μm
Shao et al. (1993)	[8]	1.1×10^{-6}	1.8×10^{-5}	TSP
AP-42 (1994)	[9]	1.1×10^{-7}	1.8×10^{-6}	Fugitive dust
This study: unstable (disturbed)	[6]	3.5×10^{-4}	5.6×10^{-3}	PM-10
This study: stable (undisturbed)	[6]	1.5×10^{-4}	2.4×10^{-3}	PM-10
Stetler and Saxton (1996)	[10]	1.0×10^{-4}	1.6×10^{-3}	Fugitive dust

Note: TSP is total suspended particulates.

(C) Identify all polygons with the general soil type, WEG, disturbed vacant land area and undisturbed vacant land area, which fall in the proximity of wind speed monitoring station 1.

(D) Select criterion for the minimum wind speed limit, v, (say, 20 mph) above which erosion and emissions occur, and identify all hours at which wind speed is greater than v mph.

(E) Consider hour 1 at which wind speed is greater than v mph. Depending on the choice selected in Step A:
- Multiply the *disturbed* area of each polygon with the flux emission factor of the corresponding general soil type or WEG. Similarly, multiply the *undisturbed* area of each polygon with the flux emission factor of the corresponding general soil type or WEG.
- Multiply the *disturbed* area of each polygon with the spike emission factor of the corresponding general soil type or WEG. Similarly, multiply the *undisturbed* area of each polygon with the spike emission factor of the corresponding general soil type or WEG.

(F) Consider hour 2 at which wind speed is greater than v mph. Depending on the choice selected in Step A:
- Multiply the *disturbed* area of each polygon with the flux emission factor of the corresponding general soil type or WEG. Similarly, multiply the *undisturbed* area of each polygon with the flux emission factor of the corresponding general soil type or WEG.
- If the time difference between the previously estimated spike emissions and this hour is *greater than* 24 h, then multiply the disturbed area of each polygon with the spike emission factor of the corresponding general soil type or WEG, and, multiply the undisturbed area of each polygon with the spike emission factor of the corresponding general soil type or WEG. (The soil is assumed to regenerate the loose material that contributes to a spike if there is a resting period greater than 24 h.)
- If the time difference between the previously estimated spike emissions and hour 2 is *less than* 24 h, then do not use the spike emissions factor. (The soil is assumed to be depleted of the loose material that generated the spike, and the depletion does not sufficiently regenerate in 24 h for the spike to occur.)

(G) Repeat Step F for all remaining hours at which wind speed is greater than v mph in chronological order.

(H) Repeat Steps C–G for all wind speed monitoring stations.

2.8. Step 8: display data or compute area-wide averages

Once results are computed for all polygons, information can be displayed either by polygon, or assigned to grid cells and displayed on a grid cell basis. Information computed for all polygons can also be summed to generate area-wide estimates of PM-10 emissions for a particular design period. A program was written in C programming language to implement sub-steps A–H in Step 7 and to estimate valley-wide PM-10 emissions for the design year.

For Clark County, NV, area-wide emissions were computed for both a design day (25 February 1999) and for the 1999 design year. Table 3 illustrates the computation of PM-10 emissions for a polygon in WEG 5 during an 8 h wind storm event. It can be seen that spike emissions are estimated only the first time when the wind speed exceeds the minimum wind speed limit whereas flux emissions are computed each time the wind speed exceeds the minimum wind speed limit. The flux and spike emissions are 0 if the wind speed is less than the minimum wind speed limit. This can repeated for all polygons in the study area and all wind storm events during the year to estimate PM-10 emissions for the study year.

3. Results and discussion

As stated previously, the land disposal boundary within the Las Vegas Valley is considered as the study area. To demonstrate the working of the methodology, vacant land area collected on 29 November 1999 during the study year 1999 was used. The disturbed vacant land area and undisturbed vacant land area were set as variables in the model. Thus, the model allows the end user to rapidly test various scenarios. In this paper, three different scenarios are tested. They are 80% of vacant land area is undisturbed or stable, 86% of vacant land area is undisturbed or stable (determined by University of Nevada, Las Vegas research team based on an analysis of construction dust permit records), and 90% of vacant land area is undisturbed or stable.

Table 3
Computation of PM-10 emissions for a polygon during a wind storm event

Polygon	WEG	Wind speed	Unstable				Stable				Total PM-10 emissions ($X+Y$)
			Area (D)	Flux emission factor (ED)	Spike emission factor (SD)	PM-10 emissions ($X=D$(FD + SD))	Area (U)	Flux emission factor (FU)	Spike emission factor (SU)	PM-10 emissions ($Y=U$(FU + SU))	
1	5	16	18	0.00000		0.00000	68	0.00000		0.00000	0.00000
1	5	23	18	0.00890	0.00243	0.20394	68	0.00749	0.00100	057732	0.78126
1	5	26	18	0.00890		0.16020	68	0.00799		0.54332	0.70352
1	5	28	18	0.00890		0.16020	68	0.00799		0.54332	0.70352
1	5	31	18	0.00136		0.02448	68	0.00749		0.50932	0.53380
1	5	37	18	0.00935		0.16830	68	0.00749		0.50932	0.67762
1	5	24	18	0.00890		0.16020	68	0.00749		0.50932	0.66952
1	5	14	18	0.00000		0.00000	68	0.00000		0.00000	0.00000
Estimated PM-10 emissions during a wind storm in polygon 1											4.06924

Note: Wind speed is in miles per hour; area is in acres; flux emission factor in tonnes/acres/h: spike emission factor in tonnes/acre, and PM-10 emissions are in tonnes; units are in US customary units (1 tonnes = 2000 pounds; 1 acre = 43,560 square feet).

Table 4 shows estimated PM-10 emissions for few sample polygons during calendar year 1999.

Results obtained for the three different cases are presented. Fig. 4 shows PM-10 emissions by WEG and general soil type for each of the three cases. Estimates show that values obtained from using WEG as the criteria are generally higher than those obtained from using general soil type as the criteria. Comparison of estimated emissions to ambient monitoring data for the design day and design year would be warranted to conclude which scenario is closest to real world data. As expected, the PM-10 estimates per year in the valley increase as the extent of disturbed vacant land area increases.

The minimum wind speed threshold, v mph, to initiate PM-10 emissions was usually assumed to be 20 mph. This 20 mph threshold was set conservatively as the 16th percentile (mean minus one standard deviation) of the 10-m threshold velocities for initiation of PM-10 erosion observed in wind tunnel tests [12]. However, this value is set as a variable in the GIS model. Thus, it allows the end user to test emission factors based on different minimum threshold values for initiation of valley-wide PM-10 emissions. Fig. 5 summarizes computed valley-wide PM-10 emissions, calculated by both WEG and general soil type, using four different wind speed thresholds for initiation of PM-10 emissions (15, 20, 25 and 30 mph, respectively) for the case assuming 86% of total vacant land area is undisturbed (stable) during any given day. Fig. 5 shows that there is a significant effect of initiation threshold on estimated valley-wide emissions.

Effects of short-duration wind gusts on estimated emissions cannot be evaluated in this model, as only hourly average wind speeds are available. Aeolian soil erosion is known to be a non-linear function of wind speed, and higher wind speeds in each averaging hour would erode more PM-10 than lower wind speeds in each averaging hour. Additionally, reservoirs of fine particles on soil surfaces may deplete over time, decreasing emissions. To improve model accuracy, wind tunnel emission factor data would need to be available over time periods longer than 10 min, and wind speed data would need to be available over time periods of less than 1 h.

The GIS model can also be used to estimate valley-wide PM-10 estimates by WEG and general soil type on any given day. The model lets the user to select the month and day for analyses. Fig. 6 shows valley-wide PM-10 estimates by WEG and general soil group for three proportions of disturbed vacant land on the 1999 design day used in the Clark County PM-10 SIP, 25 February 1999.

Fig. 7 maps spatially disaggregated 1999 design year PM-10 emissions for each grid cell of the study area, assuming 86% of vacant area is stable. The total estimated PM-10 emissions are 23,763 tonnes during the study year. Individual grid cells are shaded based on the estimated PM-10 emissions for the grid cell. Dark colors are used to show grid cells with PM-10 emissions greater than 50 tonnes during the study year. Such a map helps identify zones with high emissions so that priority for application of appropriate control measures could be assigned to high PM-10 emission areas.

Table 4
Estimated PM-10 emissions of a few sample polygons for calendar year 1999

Polygon	WEG	Unstable vacant land area (acres)	Stable vacant land area (acres)	Total vacant land area (acres)	PM-10 emissions (tonnes/year)
1	9	92	357	449	1
2	4	77	394	471	1
3	3	9	269	278	1
4	5	76	322	398	38
5	5	21	136	157	26

Note: Units are in US customary units (1 tonnes = 2000 pounds; 1 acre = 43,560 square feet).

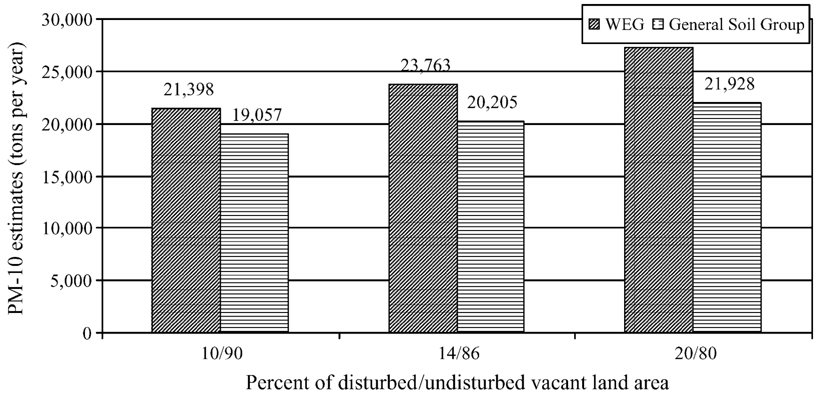

Fig. 4. 1999 design year valley-wide PM-10 estimates for different scenarios of unstable vacant land area in each grid cell.

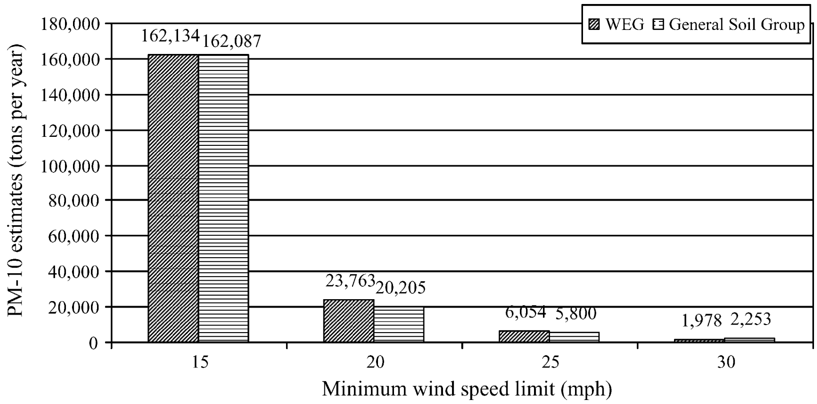

Fig. 5. 1999 design year PM-10 estimates by minimum wind speed for initiation of PM-10 emissions.

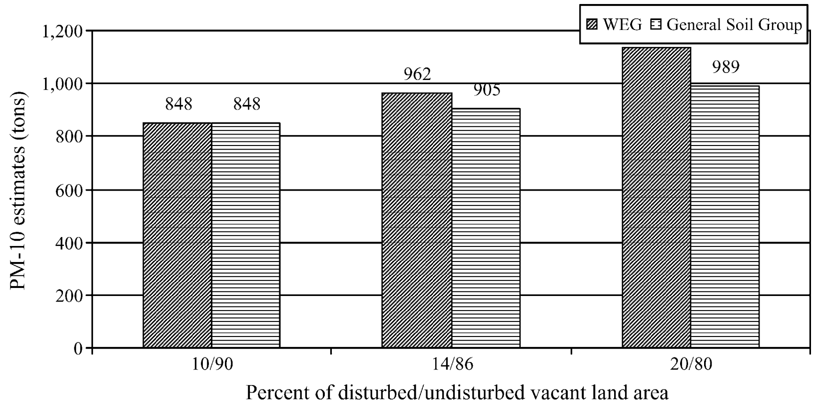

Fig. 6. PM-10 estimates for design day, 25 February 1999 by estimated percentage of unstable vacant land area.

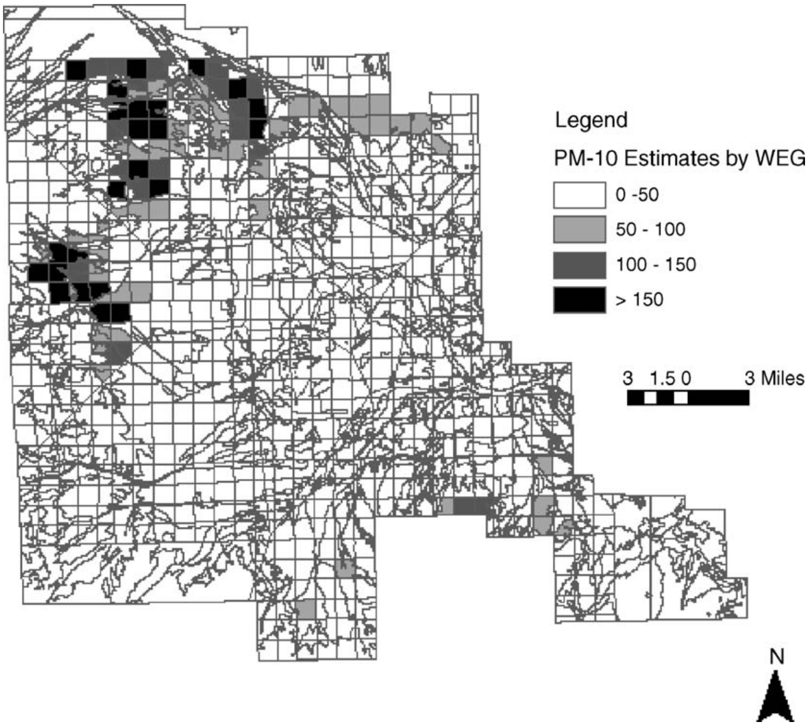

Fig. 7. Gridded map depicting spatial distribution of estimated PM-10 emissions (23,763 tonnes) for the 1999 design year, estimated based on WEG and assuming 86% stable (undisturbed) land.

4. Conclusions

Potential health hazards affecting breathing and respiratory systems due to air pollution resulting from particulate matter of size less than 10 μm could be reduced by establishing methods and strategies to control PM-10 emissions. Accurate area-wide PM-10 estimates identifying zones and causes of high emissions are essential to implement the mitigation strategies. This paper presents a GIS-based methodology to estimate area-wide design year or design day PM-10 emissions based on the extent of stable versus unstable land in the vacant land inventory, wind tunnel PM-10 emissions data classified by soil group and wind speeds, and on meteorological data for the desired design period. Results obtained by changing the percent of disturbed vacant land area/undisturbed vacant land area and the minimum threshold for initiations of PM-10 erosions are estimated.

A GIS-based model of PM-10 emissions:

(1) Allows graphical display of locations of PM-10 emissions estimates;
(2) Identifies grid cells/polygons with high emissions;
(3) Allows rapid testing of multiple scenarios for applications of controls (e.g., effects of reduction of percentage of vacant unstable land in either particular grid cells or throughout the entire area).

The validation of the methodology to replicate real world data warrants further investigation.

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